CHALLENGES OF COLD CONDITIONING AND STATIC TESTING THE SECOND ARES DEMONSTRATION MOTOR (DM-2)

Shyla Quinn
ATK Aerospace Systems
Brigham City, Utah

Larry C. Davis
NASA
Huntsville, Alabama

ABSTRACT

On August 31, 2010, a five-segment demonstration motor (DM) for the Ares program was successfully tested. A series of demonstration motors (DMs) will be tested in different conditioned environments to confirm they meet their design specifications. The second demonstration motor (DM-2) was the first “cold motor.” The motor needed to be subjected to sub-freezing temperatures for two months so that its internal propellant mean bulk temperature (PMBT) was approximately 40 °F.

Several challenges had to be overcome to make this a successful test. One challenge was to condition four field joints to get the O-rings approximately 32 °F. This would be done by applying conditioning shrouds to externally cool each field joint after the test bay was pulled off. The purpose of this conditioning was to validate the new O-ring design and allow joint heaters to be eliminated. Another challenge was maintaining temperature requirements for components in the nozzle vectoring system. A separate heating system was used to warm these components during cold conditioning.

There were 53 test objectives that required 764 channels of data to be recorded; 460 were specific to DM-2. This instrumentation had to be installed prior to conditioning, which meant the baseline process and timeline had to be modified to meet this time critical schedule.

INTRODUCTION

The next generation of space flight vehicles must be propelled by a safe, reliable, and powerful first stage motor. The Ares first stage is a “human-rated” motor capable of producing and sustaining 3.5 million pounds of thrust, equating to over 15 million horsepower, throughout its two minute burn period. This motor, as seen in Figure 1 below, measures 155 feet long and 12 feet in diameter. This five-segment solid fuel rocket was meant to be the workhorse of the Ares program.

A series of demonstration motors (DM) will be subjected to a different temperature controlled environment and then static tested. Through each of the DM’s, the motor’s performance, materials, and design features can be evaluated and design specifications verified.

This first stage motor contains over 1.3 million pounds of solid propellant, and thousands of pounds of insulation surrounded by a steel case. The entire mass needed to be cooled so that the propellant mean bulk temperature (PMBT) was 40 + 5/- 3 °F. For this effort it was imperative to have a thermal model that could accurately predict the temperature and time required to cool the motor to meet the schedule timeline.

This effort was performed under NASA contract NNM07AA75C

Figure 1. Motor Conditioning in the T-97 Test Bay

A large array of heavy duty conditioning equipment was required to condition the removable test bay with the motor inside. This conditioning equipment had to be capable of producing continuous subfreezing air temperatures for a two month period in the middle of summer.

While the motor was being chilled, some nozzle components needed to be kept warm to ensure proper nozzle vectoring. These components needed to be between 64-94 °F during conditioning and 80-88 °F at the time of static fire. For this purpose a separate conditioning cart had to run at full capacity reaching temperatures of up to 170 °F at its source. Even at these high temperatures it was still difficult to maintain the minimum temperature requirements. This was due to heat loss from leakage around the nozzle skirt. The nozzle skirt is a thin barrier of insulation that connects to the exterior of the nozzle and to the aft skirt. In order to maintain the minimum temperature in the nozzle cavity the temperature of the building had to be increased. This in turn reduced the cooling rate of the motor. This temperature "tug of war" between the two systems was a significant challenge. The solution was to add additional layers of insulation around the nozzle skirt.

The cold conditioning of the field joints to near freezing temperatures would enable the validation of a new O-ring design. This new O-ring can be subjected to colder temperatures than what is currently used on shuttle booster rockets. It would also prove that the need for joint heaters could be eliminated.

The field joints are where the motor segments are mated together. The four field joints needed to be individually cold conditioned once the test bay was removed, leaving the motor exposed to the ambient environment most notably the radiant heat from the sun. The joints were cooled with conditioned air funneled by newly designed joint shrouds around the case exterior. The O-rings temperature requirement was 32-38 °F at the time of fire. The improved shrouds were easy to install and adjust. They would also not damage the motor during static fire. The temperature and air flow speed within the shrouding was closely monitored. Another challenge was ensuring that the j-leg capture feature and insulation below the O-ring didn't to go below 35 °F at time of test.

A variety of test instrumentation was used on this motor. There were 764 data channels recorded, 460 channels were additional instrumentation just for DM-2. The instrumentation bonding compound needed be between 60-80 °F to cure. This meant that all the instrumentation had to be bonded to the motor months ahead of a normal build schedule.

RESULTS AND DISCUSSION

The DM-2 motor is so large that it must be assembled in a massive removable test bay (T-97), which measures 205 by 32 by 31 feet. Several months were dedicated to the assembly and instrumentation bonding of the five segments and nozzle assembly. The cold conditioning was initiated on July 6, 2011. When the conditioning started, the PMBT was calculated to be 78 °F. After two months of conditioning the DM-2 motor was static tested at 0927 MST on August 31, 2010, and at that time the PMBT was calculated to be 42 °F. All design parameters and program goals were met in this test.

THERMAL MODELING

To meet the static test schedule, it was crucial to have an accurate predictive model that would give an accurate assessment of the temperature and time needed to achieve the desired PMBT. This model would help the assembly and instrumentation build schedule. Prior models used to predict the PMBT did not have the fidelity needed for this test. This was mainly due to the simplicity of the models. The prior models only accounted for the motor and a small adiabatic space around the motor. These models failed to account for the multiple heat sinks including the cement floor, steel braces, and the massive cement thrust block. They also didn't account for the building's R (insulation rating) and outside temperature effects. The previous models underestimated the necessary time and temperature required to achieve the PMBT goal.

A new thermal model was developed. This new model accounted for all the above factors as well as the solar radiation on the building and thrust block. It also accounted for the radiation exchange from the surrounding terrain and sky. The model assumed a uniform thickness of the cement floor of 10 feet, where in fact the floor depth varied. A 3-D thermal "Predictive" model was generated and run in Thermal Desktop modeling code. The model looked at four input temperatures: 20, 25, 30, and 35 °F as seen below in Figure 2. However, there was a temperature limit restriction on the case being 22 °F. Another 2 °F was added to the restriction due to thermocouple error. The 30 °F and 35 °F were the most heavily weighted.

The model assumed a constant 40,000 cfm flow into the building. The model showed that it would take approximately 40 days at 30 °F and over 60 days at 35 °F to reach the PMBT goal. The model turned out to be a good conservative predictor of motor reaction, which can be seen below in the conditioning section.

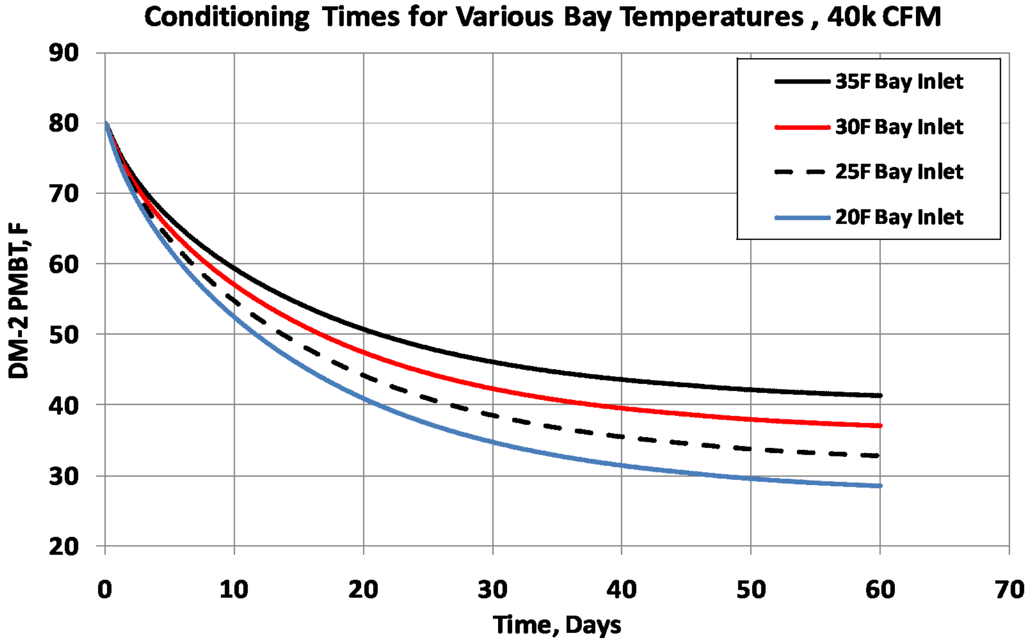

Figure 2. Predictive PMBT Model

A second model known as the operational PMBT model was simpler in its design. It took the real time data collected from the 32 thermocouples adhered to various locations along the external surface and 24 thermocouples along the internal diameter on the propellant surfaces of the motor. This model captured the thermal effects along the surfaces of the motor. This model was much more accurate than the predictive model and it could be run every day to provide real-time updates. With these updates, the conditioning in the bay would be adjusted. This model was used to calculate the final PMBT at time of static test. The results of the conditioning using the operational model can be seen in Figure 3 below.

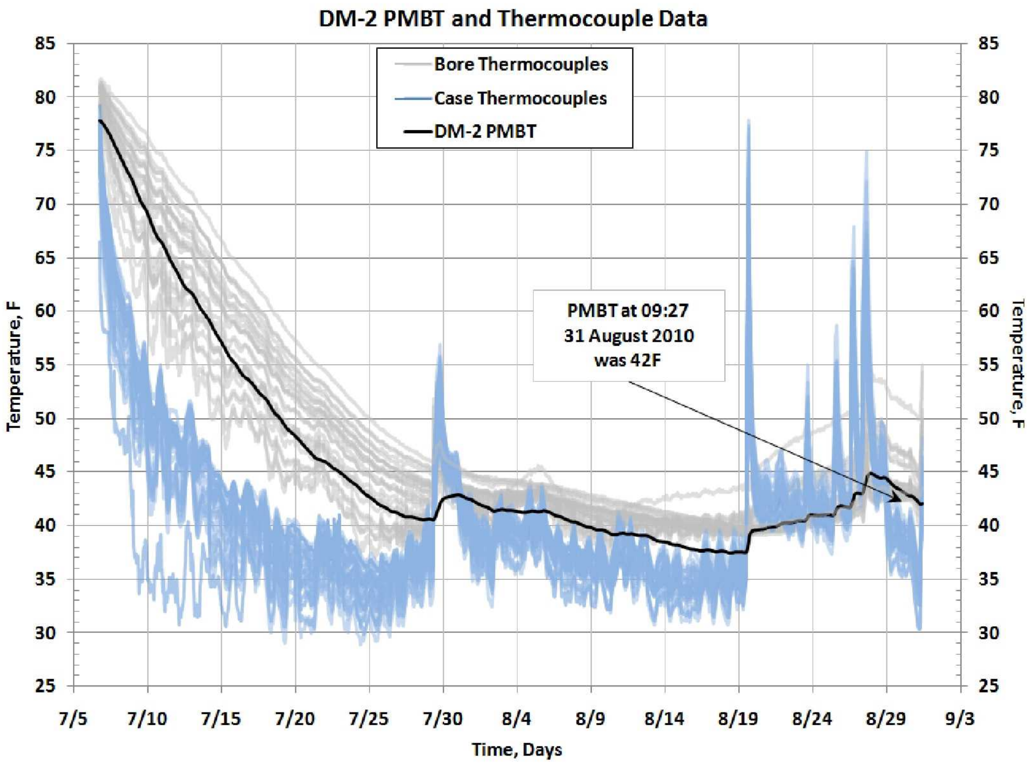

Figure 3. Actual PMBT Calculated Using Thermocouple Data

CONDITIONING EQUIPMENT

Aggreko was contracted to supply the heavy duty conditioning equipment needed for this effort. This equipment needed to be capable of supplying a constant flow of subfreezing air around-the-clock for a minimum of two months. Another requirement was that all critical equipment needed to have a back-up, in case the primary failed. It was also desired that the system could provide some adjustability so the conditioning temperature and air flow speed could be modified to meet changing conditions.

The conditioning equipment setup seen below in Figure 4 consisted of: two 200 ton chillers filled with a 50% propylene glycol solution called “brine”. This brine solution could go to -10 °F if needed. When the brine solution was cooled to this temperature it lowered the capacity of the chillers to approximately 85 effective tons. The original setup had only one chiller running with the other acting as a backup. However, because of the heating throughout the day and the building’s response, both chillers were run throughout the full two months. The brine solution was pumped through 6 inch hoses using two 1000 gallon per minute pumps.

Figure 4. Conditioning Equipment Set-up at T-97

The cold air was blown into the building by seven 120 ton Air Handler Units (AHU). The building was separated into three segments with inlet and return ports. Six AHUs were configured in a double stack configuration. The AHUs are essentially huge fans that pull in air and moisture from the building. The air is then blown over coils containing the chilled “brine” solution. The air is blown back into the building via the inlet ducts. As conditioning efforts progressed, it was determined that the best and easiest way to modify the inlet temperatures was to adjust the airflow rate of the AHUs. The slower the rate, the longer the time the air had to be chilled over the coils and thus the colder the air. Inversely the faster the airflow rate the warmer the air would be. This way the three sections of the building could be adjusted to ensure an even cooling of the motor. The motor cooled down at different rates, the subtle adjustments of the inlet temperature were vital. The last air handler was for the fresh air supply to the building. It was connected to a 5000 cfm dehumidifier and a 20 ton air conditioner. This set-up was later used to condition the joint shrouds discussed later in this paper.

The double stack design was key for maintaining a continuous flow to the building. The coils for the brine solution kept freezing. This was because of the humidity and temperature differences between the coils and the air. As the ice started to buildup, the air flow would become impeded. Because the two AHUs were double stacked, one of the pair could always be in defrost. The technician would shut off the air flow and reroute the brine solution to the other air handler and start running hot water running through the frozen coils. This cycling between the two air handlers was usually done every 2 to 6 hours. The hotter the day the more frequently the coils would freeze up. Generally at night when the temperatures were much cooler the air handlers only had to be switched one or two times.

All seven air handlers were setup to run off of the facility power at T-97 via three power stanchions. The chillers, pumps, air conditioner, and humidifier were powered by two 500 KW diesel generators. Both generators were running approximately 50% capacity at all times. A 2,300 gallon double walled diesel tank supplied fuel to the generators. This tank needed to be filled every 2 to 3 days. Even though the power to the AHUs was supplied by the facility power, a preventive measure was enacted in case of a power blackout. Additional backup cabling was preinstalled so that all the conditioning equipment could be run off the generators if necessary. This act of foresight proved invaluable. During conditioning the power to the facility was lost twice. When these power outages occurred the conditioning efforts were reinstated by switching to the generators within an hour.

BUILDING MODIFICATIONS

The T-97 test bay is designed so that it can be rolled back to expose the entire motor for static test. There are two underground rooms (25 by 14 by 10 foot) called aft pits. Both pits are used to route cabling from the motor through a series of underground tunnels to an array of data collection computers. The furthest aft pit contains the aft test stand. This hydraulic test stand is used to aid in motor restraint and to measure thrust vector as the nozzle undergoes its actuation cycle. It was known ahead of time that closing off of these aft pits would be imperative. Since cold air sinks, having an open pathway for the air to flow out would have made maintaining conditioning in the building nearly impossible. Insulative thermal blankets were used to seal off the openings in the floor leading to these pits. However, this measure had limited success. The blankets had to be moved out of the way for cables to be run into the pits. The major mitigation was the installation of doors and thick cork barriers in any opening leading from the pits to the tunnels. Where needed the cabling was run through the cork. These measures minimized the temperature losses.

The forward thrust block is a massive cement block that acts as the primary flight restraint for the motor. Because the building requires periodic removal, a large gap exists around the entire thrust block. The largest gap was directly above measuring approximately four feet high. Two layers of insulative thermal cement blankets were used to close off the gaps. The blankets were secured to the building and around the thrust block. This proved to be highly successful for insulating the building in that area. Whenever the building needed to be pulled back the blankets would be lifted up and secured on hooks installed on the building's exterior.

Nearly a year before the conditioning effort for DM-2 commenced, the facility underwent a major overhaul. The existing aft ducting was far too small and was connected to the center inlet ports. The building was modified so that the aft section had its own inlet and return ports. The ducting was replaced with bigger ducting able to accommodate a 20,000 cfm flow rate. The ducting was also extended around and over the aft roll up door.

During this renovation it was discovered that the fresh air supply had been tied into the return air supply. The ducting was rerouted ensuring that a dedicated fresh air supply was provided into the building. The inlet and return ports were fitted with adapters able to connect the 24-inch insulated ducting provided by Aggreko to their air handlers. These adapters had to have several layers of insulation applied to prevent significant thermal temperature loss and ice build-up. This eliminated a potential safety issue.

The test bay already had its own heating system located above the motor. This system works by heating air with steam lines and using fans above the motor to blow air down into the building. Stratification was a big concern and has been a problem for other conditioned motors. In order to help mitigate this stratification the fans were turned on to help circulate the air. This measure did reduce the stratification by over 50% and helped reduce the temperature variances from side to side of the building.

CONDITIONING

The main conditioning started on July 6, 2010, the PMBT was calculated to be 78 °F. In order to prevent the formation of condensation and ice buildup on the motor and metal test stands, the inlet temperature set point was gradually reduced over a period of a couple of days till it was at 35 °F. This allowed the building to gradually cool while the moisture was being drawn out by the air handlers. The building was left at 35 °F for a short time then the set point was reduced to 28-30 °F.

In the beginning, the set point couldn't go lower than this range for two reasons. First, the location of the air vents meant cold air was being blown directly onto the motor. This was causing localized cold spots. One of the design requirements was that the metal case could not go below 22 °F. However, due to the inherent thermocouple (TC) error the temperature restriction was increased to 24 °F. The temperature difference between the localized cold spots and the rest of the motor case was several degrees. Second, the outside environment in July and August are typically the hottest months of the year in Utah, with average temperatures between 90-100+ °F. The heat of the day and the sun bearing down on the hoses containing the chilled "brine" solution made it difficult to maintain steady inlet temperatures. Consequently, as the day progressed, the inlet temperatures fluctuated as much as 10 °F even with both chillers running at maximum capacity.

Two corrective measures were implemented that greatly enhanced the conditioning efficiency. A layer of aluminum foil bubblewrap was placed over the conditioning hoses. This bubblewrap has a high reflectivity value and repelled most of the heat from the sun and insulated the cold from the hoses. The foil bubblewrap was also used as air flow barriers over each vent. These barriers prevented the air from blowing directly on the motor. Instead the air flow was directed up and down into the test bay. This eliminated the localized cooling concern. Another benefit from these barriers was it reduced the stratification within the building by half. Once the localized cooling and equipment issues were resolved, the conditioning of the building became much easier to regulate and colder temperatures could be achieved.

The motor cooled unevenly, with the aft section cooling faster than the forward. This was because the aft was dominated by the nozzle that cooled faster than the insulated propellant. At first the forward end of the motor was more resistant to cooling. It would retain its temperature and then have small incremental temperature drops. These incremental drops evened out as the whole of the motor started to reach equilibrium. This equilibrium was reached due to the careful modulation of the conditioning through the three segment areas of the building. The forward segment was always kept slightly colder than the other two segments. Another factor that helped to even the motor temperature throughout segments was during the first aft roll up door opening. The aft end warmed up more quickly so when conditioning was reinstated it more closely matched the forward section. This equilibrium was maintained throughout the rest of the conditioning period.

There were several scheduled door up, building “off dates” planned throughout the conditioning to accommodate pretest activities. The first time the aft roll up door was opened during conditioning was to allow for the alignment of the side load fixture. The laser tracking system used for this effort required a minimum of 50 °F in order to function properly. The alignment was scheduled to occur in the morning to reduce the temperature difference. This would reduce the amount of condensation and heating of the motor. There were no previous data regarding how the motor and test bay would react and how much condensation would accumulate when exposed to a much warmer environment. This was a valuable learning exercise as well. The thermal analysis estimated that the motor would only change one degree, because the building would remain on.

The conditioning equipment was turned off at 7 a.m. and the aft roll up door lifted. It was anticipated that the forward section would heat up slowly, while the aft would quickly acclimate to the ambient conditions. This was not the case. The entire building increased in temperature rapidly going from just below 30 °F to almost 60 °F almost instantly. This rapid heating caused condensation to form on anything metal immediately. The forward section saw the most condensation due to the massive steel forward test stand. The bay floors had to be mopped continuously to avoid any safety issues. Condensation had always been expected but the extent of how much was a surprise. The building was closed up once the alignment was completed around 1100 MST.

Reinstatement of the conditioning was constrained by a design specific nozzle issue. One of the joints within the nozzle utilizes a carbon fiber rope (CFR) placed in a grove to impede any potential gas paths during firing. The concern wasn’t with the water itself, but the potential of the water freezing in the rope. The concern was that if ice had formed, it would instantly turn to steam at static test. There were no data to ensure that the rope would perform as expected under these conditions. The CFR had to be dried out before conditioning could continue. Three thermocouples were installed next to the groove. The conditioning cart was used to dry out the groove from the inside out. The TCs were used to monitor temperatures to ensure the CFR never went below 35 °F.

The conditioning was reinstated at the end of the day at 1630 MST. The inlet set point temperature was initially set for 40 °F. It was then slowly lowered over a period of days to 35 °F. The day the motor was left without conditioning its PMBT increased three degrees. This was three times more than expected. The building’s set point remained at 35 °F until the CFR was dried out. However, the 35 °F restriction on the CFR remained in effect throughout conditioning. This condensation issue did lead to some improvements in the overall conditioning of the motor. Even though the door up/building off schedule was made to minimize the amount of times conditioning was turned off, the schedule was refined even more. The main corrective measure was to keep the conditioning equipment running while the roll up door was lifted. The conditioning equipment would allow the building to slowly acclimate. After this corrective measure was employed, condensation events were eliminated.

It is important to note that every time the door was rolled up or the building pulled back, it took several days to get the building back down to 30 ° F. The motor warmed up quickly, especially when exposed to direct sunlight.

Another conditioning challenge was the tug of war between the main conditioning of the building and the heating of the nozzle cavity. The rubber material must be kept warm, between 64-94 °F, to ensure that the components responsible for actuating the nozzle can bend and flex. To keep the internal components warm a protective insulative barrier called a “nozzle skirt” was is installed around the nozzle. Heated air was blown in and circulated around the nozzle cavity. Before the conditioning effort began, the aft skirt conditioning cart was moved outside the building. This was done because the conditioning cart would not be able to be as efficient in a cold environment. Also, the heat released from the cart would interfere with the cold conditioning for the aft end of the bay. The conditioning cart had to be run at full capacity; reaching 170 °F at its source. However, it was having trouble keeping the nozzle cavity in its acceptable temperature operating range. The solution was to increase the insulation of the nozzle skirt. This allowed the nozzle components to stay warm even when the building’s inlet setpoint temperature reached 22 °F.

The various temperature restrictions combined with the need to roll the bay back to perform essential activities near the end of conditioning meant the motor’s PMBT was slightly out of the program’s goal range. Because the nozzle heating corrective actions had proven successful, the inlet set point temperature was dropped to 25 °F and later to 22 °F for the last three days. The TCs on the motor case never fell below the 24 °F. The three days of dedicated cooling did allow the PMBT of the motor to drop to just above 40 °F. The day of static test the building was pulled off just before sunrise. Once the building was pulled back the joint shroud conditioning was activated. Figure 5 shows the motor getting ready for static test approximately T-2 hours. At T-60 minutes the joint conditioning was turned off. At the time of test the PMBT was calculated to be 42 °F.

Figure 5. Pretest Picture

JOINT SHROUDS

The four field joints needed to be conditioned so that the O-rings could be 32-38 °F at the time of test. However, the j-leg feature and insulation inboard of the O-rings should not go below 35 °F. A thermal analysis was conducted to predict the reaction of joints once the motor was exposed to the environment. Figure 6 below shows the prediction of how quickly the joints would heat up once the sun came up and radiant heating began. The analysis shows that even with active conditioning, the warming of the motor outside of the shrouds would eventually warm the joints beyond the temperature limits. Figure 6 shows the predictive thermal analysis of the joint shrouds for the day of test.

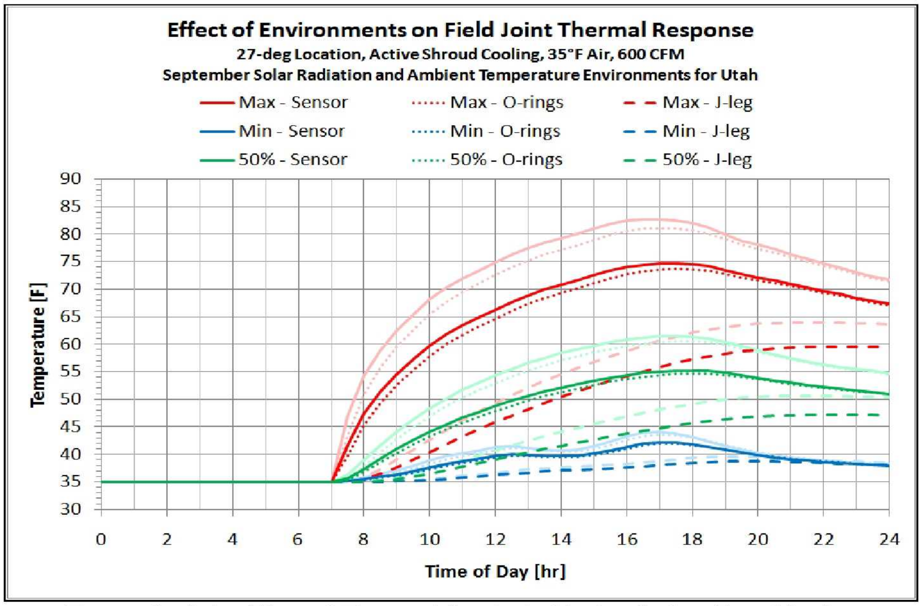

Figure 6: Joint Shroud Thermal Analysis Under Active Conditioning

The four field joints had to be individually conditioned externally using air so that the O-rings would be cooled first and the other features could remain 35 °or above. Previous attempts to shroud and condition the field joints resulted in bulky, expensive metal shrouds that didn't fit well and could possibly damage the motor case during static test.

The new shrouds were designed to be easily applied, lightweight, and flexible. The shroud components were bonded to the case so no damage would occur during test. The shrouds consisted of five simple elements: aluminum braces, shrouding material, inlets, electrostatic dissipative ducting, and the air flow manifold. A simple schematic of the joint shroud set-up can be seen in Figure 7.

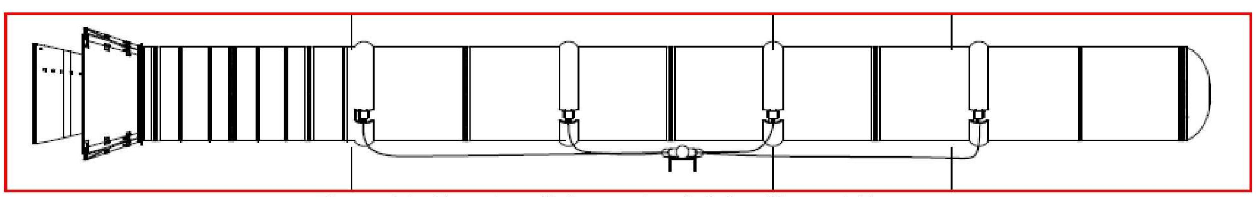

Figure 7: Drawing Schematic of Joint Shroud Set-up

The aluminum braces are seen in Figure 8 below. The braces acted like ribs providing structure for the shrouds. They were bent to form a semi-circle with flanges on the end. The braces were designed to span a minimum of 13 inches on each side of the field joint. Strong 139 lb magnets were bolted to each of the legs and secured to the motor.

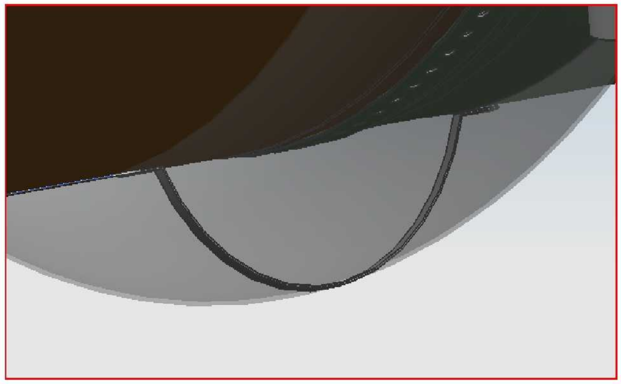

Figure 8: Representation of Internal Shroud View

The air inlets were also made of aluminum. They were designed to be 12 inches in diameter to ensure the appropriate flow rates could be achieved. The inlets were held to the motor case by eight 139 lb magnets.

The inlets were connected to electrostatic dissipative ducting. This ducting was chosen because it was acceptable to temperatures down to -20 °F. It was designed to dissipate all electrostatic charge via a bronze coated steel wire imbedded within the thermoplastic polyurethane. Solid propellant is sensitive to electrostatic discharge. All the material and the processes used for conditioning had to be with the highest levels of safety.

The shroud material was an aluminum foil bubblewrap. This material was chosen because it is thin (approximately .25 inch), lightweight, and flexible. It had a good insulation rating and could reflect 97% of the radiant energy. Since the sun was the primary source of heating this feature was essential. The aluminum foil bubblewrap was capable of performing well to -4 °F. The shrouding material was laid over the brace and then secured to the steel case by high strength aluminum foil tape. The tape had a high adhesion to steel rating and was acceptable for use to -65 °F. The shrouding material and tape option proved to be an excellent method of shrouding and conditioning the field joints.

The static dissipative ducting was connected to an aluminum air flow manifold. The manifold was designed to take in the conditioned air from the Aggreko air handler unit and flow it out to the four joints. The manifold had air flow regulators that could be manually adjusted to control the amount of air to each joint. Since the joints were at varying distances from the manifold, the air flow had to be manually balanced using an air flow manometer. An example of this can be seen in Figure 9 below.

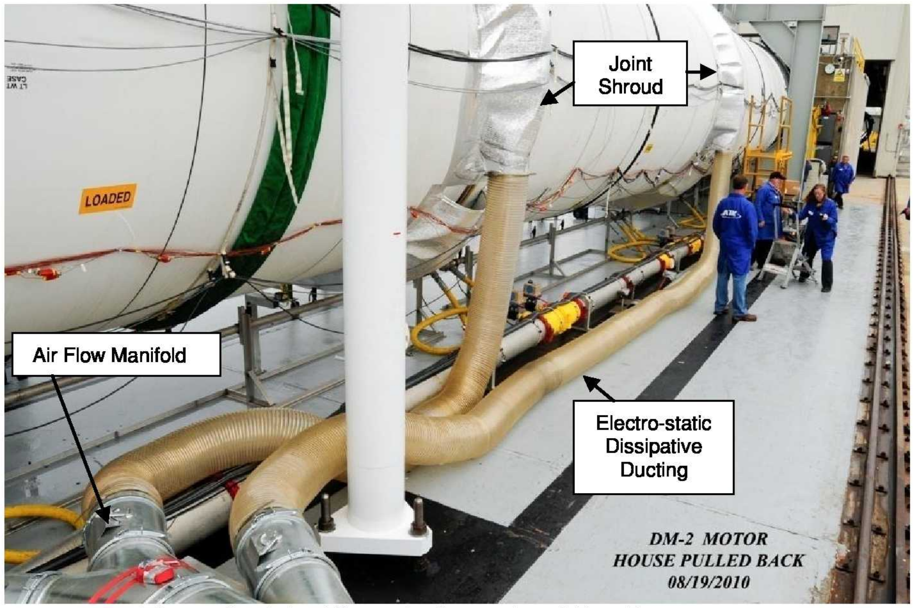

Figure 9: Joint Shrouds Operational Dry-Run

The joint shrouds functioned extremely well. The conditioning was terminated T-60 minutes prior to test per the countdown script. The thermocouples imbedded in the joints reported O-ring temperatures between 32.5-36 °F at the time of static test.

INSTRUMENTATION

There were a total of 764 data channels, 304 channels were standard instrumentation and 460 were added to support DM-2 test objectives. This test became the largest amount of data channels used in ATK's history. There were 95 accelerometers installed on this motor. The accelerometers were used to help measure the dynamics and loads on the motor.

In addition, displacement instrumentation such as extensometers, longwire gages, and linear variable displacement transducers (LVDTs) were used to measure motor sag, nozzle joint movement, and field joint movement. Eroding potentiometers and ultrasonics were utilized to measure the erosion rates of the exit cone and aft segment.

A series of transducers were used to measure the internal pressure of the motor, igniter, deluge system, and thrust vector control system (TVC). Most of the strain gages were devoted to measuring the nozzle and aft exit cone. A few girth gages were installed on each segment of the motor.

There were a total of 234 temperature sensors installed throughout the motor. These sensors were primarily composed of thermocouples (TCs) and resistance temperature detectors (RTDs). They were used to measure the metal case, internal insulation, propellant nozzle, and all joint temperatures. The measurements from these sensors were used to verify the thermal operation requirements, internal field joint, and deluge temperatures as well as calculate the PMBT of the motor.

Several radiometer sensors were setup outside the test bay to measure the heat flux from the exiting plume from the aft exit cone.

SAFETY AND PEOPLE

With personnel working in the building for 8+ hours it was necessary to train employees on how to identify and treat symptoms related to working in extreme temperatures. A particular concern was thermal shock, which is caused when transitioning quickly from one environment to the other. Due to this heightened awareness there were no health or safety issues.

SUMMARY AND CONCLUSIONS

The first stage Ares rocket motor is an improvement of the reliable human-rated RSRM boosters used to launch the space shuttle. In order to test the effectiveness of these improvements, the motors will be subjected to a variety of conditioned environments. The second demonstration motor (DM-2) was cooled under subfreezing temperatures so that its propellant mean bulk temperature was (PMBT) was 40 +5/-3 °F.

This conditioning effort was an enormous task that took a year of careful planning and coordination. Heavy duty conditioning equipment was brought in to provide around-the-clock conditioning to the test bay. The conditioning effort took place in the middle of summer and lasted two months. The conditioning equipment setup was designed to have built in redundancy. This meant that a continuous supply of conditioned air was delivered to the test bay while some of the equipment was down for defrost or scheduled maintenance.

A new thermal analysis was created to help define the minimum requirements needed to achieve the PMBT goal within the allowed two month time period. The new model took into account the multiple heat sinks within the test bay and motor. The model also included the insulation factor of the test bay itself and the outside temperatures generally associated during the two summer months of conditioning. This model was used to help develop a test schedule for the essential pre-test activities and was found to closely model the actual conditioning results.

Stratification, which has been a concern for previous static tests, was successfully mitigated. Existing blowers located above the motor were activated. This allowed the conditioned air to be circulated throughout the bay more efficiently. This reduced the stratification by an order of four times. The stratification was further reduced when air barriers were installed over the inlet ports.

In case the power to the facility was lost. Additional cables were already pre-routed so that the conditioning equipment could all run off the generators. This preventive measure allowed for the conditioning to be reinstated quickly when power was lost twice.

Some valuable lessons learned include the use of aluminum foil bubblewrap for covering the conditioning hoses. These hoses transported the brine solution from the chillers to the air handlers. During the course of the day, the sun heated the hoses enough to significantly affect conditioning. The foil bubblewrap was used to reflect most of the radiant energy from the sun and provide additional insulation for the hoses. This aided the conditioning equipment to keep to air temperatures to the building more consistent and put less stress on the equipment. Another use for the bubble wrap was to make air flow barriers over the air inlet ports. The barriers blocked the direct airflow on the motor, which eliminated localized cold spots on the motor.

Condensation was found to be more severe than expected. The first time the aft roll up door was opened and conditioning turned off, the formation of condensation was instantaneous and severe. The corrective action was to keep the conditioning equipment running while the door was opened. This helped by slowly acclimatizing the motor and test bay to the ambient environment, effectively reducing the formation of condensation to negligible levels.

Working in cold environments posed additional safety and health issues. This was intensified when personnel had to transition from cold to hot temperatures rapidly. Training was used to educate personnel to know the warning signs and identify the best way to work in the different environments.

An accelerated schedule had to be developed to ensure the bonding and installation of 764 channels of instrumentation. The routing of cables and checkout of the instrumentation was conducted during the two month conditioning. Other pre-test activities such as test stand calibration, hydrazine stand set-up, and quench system checkout required the building to be pulled off or the roll up door opened. This caused the motor to warm up faster than the initial analysis showed. Because of this warming the last three days were dedicated to conditioning only. The test bay inlet temperatures were dropped to as low as 22 °F. This allowed the motor to cool down until the PMBT was well within the desired temperature range.

FUTURE WORK

The next demonstration motor (DM-3) will be a “hot motor.” It is currently scheduled for static test in September 2011. The program goal for PMBT is 90+/-5 °F. Current plans are to heat the T-97 test facility solely utilizing the existing heating system situated directly above the motor. Issues with stratification and uneven heating of the motor are being reviewed.

ACKNOWLEDGMENTS

I would like to thank all the folks at Aggreko who did a great job in a professional manner. A special thanks to Robin Henry, Steve Bukoski, LeRoy Green, and Beau Peckham.
Thanks to the following people of ATK: Marc Hernandez and Brett Verhoff (thermal analysis), Jessica Widrick (Seals), Mauren Froerer (Tooling), Heather Wokurka (Instrumentation), Max Moore, Gary Bates, Kevin Rees, and Curtis Wise (Test Service Management).

Thanks to the following people at NASA: Louie Clayton, Tim Kibbey, Tim Lawrence, Andy Schorr, and Alex Priskos.